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SURFACE MODIFICATION TECHNIQUES FOR DENTAL IMPLANTS

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ABSTRACT

Surface finishing of dental materials significantly influence their functional properties, biological compatibility, and long-term clinical performance. Given the diversity of materials used, including ceramics, metals, polymers, and bioactive composites—each material type necessitates a tailored approach to surface layer modification. This review focuses on the classification and analysis of primary surface finishing methodologies applied to dental materials. Mechanical techniques aimed at increasing micro-roughness are described alongside chemical methods targeting surface property alteration. Physical processes such as plasma activation and laser texturing are also examined. Attention is dedicated to treatments enhancing surface bioactivity, including the deposition of bioactive coatings and chemical surface functionalization. The study emphasizes the correlation between applied surface modification techniques, resultant changes in surface topography, and biological responses within the oral environment. Moreover, the necessity of customizing technological approaches based on specific clinical requirements is underscored. The insights gained provide guidance for the optimal selection of surface finishing according to material type and intended clinical application

Keywords: surface finishing, modification, techniques, dental implant.

INTRODUCTION

Dental implants represent one of the most significant advancements in modern dentistry, enabling the restoration of function and aesthetics in patients with tooth loss. The success of implantation, however, depends not only on surgical performance and proper system selection but also—critically—on the implant's ability to achieve stable and long-term integration with bone, known as osseointegration. This ability is strongly influenced by the implant surface properties, which result from specific surface treatments. Research in implantology over the past decades has demonstrated that surface topography, chemical composition, and structure significantly affect cellular behavior in direct contact with the implant, thereby determining the quality and speed of osseointegration (Albrektsson et al., 1981; Gittens et al., 2014; Wennerberg & Albrektsson, 2009). While earlier implants featured smooth, machined surfaces, current trends focus on active and biofunctional surfaces that not only passively support bone growth but also actively stimulate cellular adhesion, proliferation, and differentiation (Rupp et al., 2006).

The aim of this review article is to analyze existing dental implant surface treatment techniques in detail, explain their principles, advantages, and limitations, and connect them to clinical application. Special attention is given to the relationship between surface modification and biological response in the peri-implant environment.

CLASSIFICATION AND PRINCIPLES OF SURFACE MODIFICATIONS

Dental implant surface treatment techniques can be classified based on their mechanism of action into four main categories: mechanical, chemical, physical, and bioactive (biological) modifications. Each of these categories affects the implant surface in a specific manner, modifying its topography, chemical composition, and biological cell response. The primary goals of these treatments are to enhance osseointegration, accelerate healing, and ensure the long-term functionality of the implant.

Mechanical Modifications

Mechanical techniques are based on the physical modification of the surface using abrasive or etching procedures. The most common methods include sandblasting with aluminum oxide or titanium oxide particles, which increase surface microroughness and improve mechanical anchorage of cells. Combining this with acid etching (e.g., HCl, H_2SO_4)—known as SLA (Sandblasted, Large grit, Acid-etched) treatment—results in a dual-level topography that positively influences osteoconductivity.

The advantages of these techniques include their simplicity and well-established clinical performance; however, potential disadvantages include residual abrasive particles or surface heterogeneity (Buser, et al., 2004).

Figure 1. Surface Modifications of Implants (Lu et al., 2023).

Chemical Modifications

These modifications alter the chemical composition or reactivity of the surface through chemical reactions, oxidation, or anodization. For instance, alkaline treatment of titanium with sodium hydroxide creates a surface layer rich in hydroxyl groups, which supports apatite formation in simulated body fluids (SBF). Anodization produces a porous titanium oxide layer of varying thickness and charge, enhancing its ability to bind Ca^{2+} and PO_4^{3-} ions. These chemical modifications are particularly significant for promoting osteoinduction and can be combined with additional functional groups (e.g., carboxyl, amino) (Kokubo, & Takadama, 2006).

Physical Modifications

Physical techniques modify the surface using physical forces, often without direct material contact. Plasma treatment utilizes ionized gas to remove organic contaminants and increase surface hydrophilicity. This improves protein and cell adhesion, accelerating the onset of osseointegration. Laser texturing allows precise creation of microstructures that guide cell growth and vascularization at the implantation site. These techniques provide a high degree of control over surface topography without compromising the structural integrity of the implant (Sul, et al., 2002; Scarano, et al., 2003).

Bioactive and Biological Modifications

Bioactive modifications go beyond physico-chemical changes and involve the application of materials that actively stimulate biological responses. These include hydroxyapatite coatings, bioactive glasses, collagen layers, peptides (e.g., RGD sequences), growth factors (e.g., BMP-2), or antimicrobial agents (e.g., chlorhexidine, silver). Such layers can be applied via methods like sol-gel processing, electrophoretic deposition, or chemical bonding. The goal is not only to enhance cell adhesion but also to direct cell differentiation and suppress inflammatory responses (Canullo, et al., 2017; Hench, 2006).

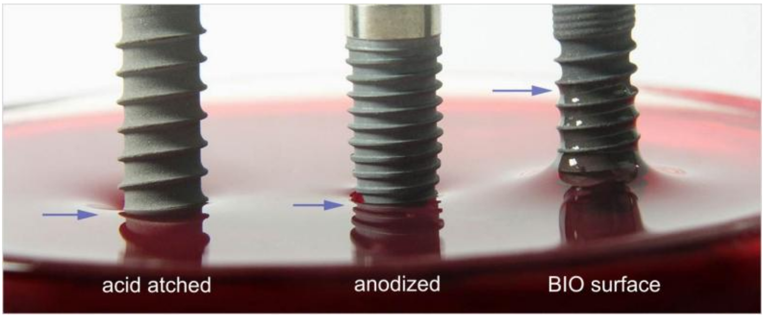

Figure 2. Comparison of liquid contact with implant surfaces: etched, anodized, and bioactive. (Dental Surgery Channel, 2019).

MECHANICAL MODIFICATIONS: MICRO- AND MACRO-TEXTURING

Mechanical surface modifications represent one of the oldest and most widely used approaches in dental implant surface engineering. Their primary goal is to enhance the topographic complexity of the surface, thereby improving its mechanical and biological properties, especially during the early phases of osseointegration. Micro- and macro-texturing increase the overall contact area between the implant and bone, which leads to better load distribution, enhanced fibrin network adhesion, and stimulation of osteoblastic activity.

Micro-Texturing

Micro-texturing focuses on creating microscopic surface irregularities ranging from a few micrometers to several tens of micrometers. These microstructures support cell adhesion, proliferation, and extracellular matrix organization. The most commonly used micro-texturing techniques include:

- Sandblasting: This technique involves treating the implant surface with a high-pressure stream of abrasive particles (e.g., aluminum oxide, titanium oxide). It produces stochastic surface roughness and increases surface energy, promoting better osteoblast attachment (Wennerberg, & Albrektsson, 2010).
- Acid-etching: The use of strong acids (e.g., HCl, H_2SO_4, HF) causes selective corrosion of the titanium surface. This process creates pits and microcracks that enhance cell adhesion and improve the biological response (Buser, et al., 1991).
- Combined Techniques – SLA (Sandblasted, Large Grit, Acid-Etched): This technique combines coarse-grit sandblasting with subsequent acid-etching, resulting in the so-called SLA surface. It has become the gold standard in commercial titanium implants. SLA surfaces demonstrate high osteoconductivity, faster osseointegration, and favorable clinical outcomes (Schüpbach, et al., 2005).

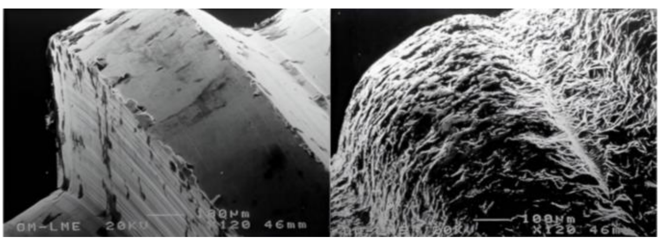

Figure 3. Implant surface before and after sandblasting (Dental Surgery Channel, 2019).

Macro-Texturing

Macro-texturing is performed on the scale of hundreds of micrometers to millimeters and affects the design of the entire implant. It includes features such as thread geometries, grooves, collars, and porous structures that enhance primary stability and enable improved biomechanical anchorage in the bone. Although macro-texture does not have as direct an effect on cellular response as micro-texture, it plays a key role in load transmission and in preventing micromovements that could disrupt the healing process (Mangano, et al., 2015).

Recent advances in 3D printing (additive manufacturing) enable the fabrication of macro-porous titanium structures that mimic the trabecular architecture of natural bone. These implants offer not only excellent mechanical integrity but also provide space for vascular and osteogenic cell ingrowth, thereby promoting so-called vascularized osseointegration (Mangano, et al., 2015).

Synergistic Potential with Other Techniques

Currently, combinations of mechanical techniques with chemical or physical modifications are increasingly used, leading to a synergistic effect. For example, surfaces with micro-roughness created by sandblasting can be further plasma-treated to enhance hydrophilicity or coated with a bioactive layer, resulting in an implant with optimized mechanical and biological performance (Gomez-Florit et al., 2021).

CHEMICAL METHODS: SURFACE REACTIVITY AND BIOACTIVITY

Chemical surface modification methods represent an important group of techniques that allow targeted alteration of the chemical composition and functional groups of the implant surface without significantly changing its macroscopic structure. Their goal is to enhance the bioactivity of the surface, improve its affinity for biological molecules, promote apatite formation, and optimize interaction with host tissue. Unlike purely mechanical techniques, these methods can create chemically active surfaces that act as “biological signals” supporting cell adhesion, proliferation, and differentiation.

Alkaline and Acid Treatments

One of the most widely used chemical methods is alkaline etching of titanium using strong bases, most commonly sodium hydroxide (NaOH). This treatment leads to the formation of a hydrated sodium titanate layer rich in –OH groups. These hydroxyl groups increase surface hydrophilicity and provide a favorable environment for apatite nucleation in simulated body fluid (SBF) (Kokubo, & Takadama, 2006). Similarly, acidic etching solutions (e.g., H_2SO_4, HCl, HF) are also used, producing fine microtubular or pitted surface structures on titanium while simultaneously activating the surface chemically. A combination of these methods (e.g., alkaline-acid treatment) is used to achieve a synergistic effect of roughness and chemical reactivity (Sul, et al., 2002).

Anodic Oxidation

Anodization is an electrochemical method in which a titanium implant is subjected to a controlled oxidation process in a conductive electrolyte under applied voltage. This process produces a porous titanium dioxide (TiO_2) layer whose properties—thickness, porosity, surface charge—can be precisely tuned by modifying the process parameters (voltage, electrolyte type, duration). The porous TiO_2 enhances surface energy, ion exchange capacity, and bioactivity (Macak, et al., 2007; Popat, et al., 2007).

In some cases, anodization can lead to the formation of nanotubular structures that serve as carriers for drug delivery, growth factors, or antimicrobial agents, thereby combining chemical surface modification with a therapeutic function (Nobel Biocare, n.d.).

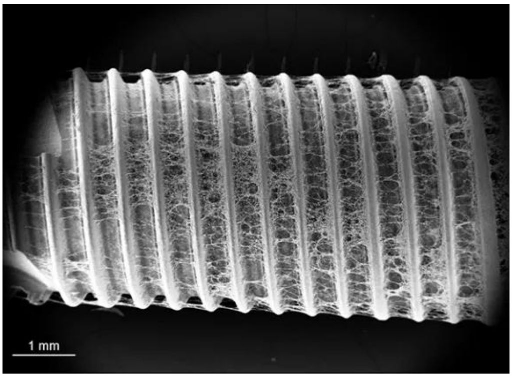

Figure 4. Anodic oxidation of the implant surface (Nobel Biocare, n.d.).

Chemical Deposition of Bioactive Compounds

Another group of techniques involves the direct chemical deposition of bioactive agents onto the implant surface. This includes:

- Deposition of hydroxyapatite (HA) using methods such as sol-gel processing, wet chemical deposition, or electrophoretic techniques. These coatings promote osteoconduction and accelerate the mineralization of the bone matrix.
- Immobilization of bioactive molecules—such as peptides (e.g., RGD sequences), proteins (e.g., fibronectin, vitronectin), or growth factors (e.g., BMP-2, TGF-β)—which are chemically bound to the activated surface via silane bonds, carboxyl, or amino groups. Such surfaces provide specific bioactive cues that stimulate cellular responses and differentiation (Schliephake, et al., 2009).

Chemical Functional Modification

Advanced chemical techniques also include the addition of functional groups or nanomaterials that alter the surface charge, polarity, and reactivity. For instance:

- Surfaces modified with carboxyl (-COOH) or amino ($-NH_2$) groups improve interactions with extracellular matrix proteins and stimulate osteoblasts (Park & Lakes, 2007).
- Nanocrystalline calcium phosphates applied as surface coatings enhance natural mineralization (Barrère, et al., 2003).

These chemical modifications can also influence the presence and orientation of adsorbed proteins, which is crucial for subsequent cell interaction (e.g., adsorption of fibrinogen, albumin, and vitronectin).

PHYSICAL TECHNIQUES: ENERGY-BASED BIOACTIVATION

Physical techniques for dental implant surface modifications utilize various forms of energy (plasma, laser, UV radiation) to modify surface properties without altering the bulk structure of the material. These methods primarily aim to increase surface energy, alter chemical composition of the surface layer, remove contaminants, improve hydrophilicity, and enhance bioactivity. They are particularly valuable for modifying the surfaces of titanium, ceramics, or polymers without mechanical disruption.

Plasma Treatment

Plasma treatments are among the most widely used physical techniques, exposing the implant surface to low-temperature plasma generated from various gases (e.g., argon, oxygen, nitrogen, ammonia). This process modifies the chemical and electrical properties of the surface through interaction with ionized particles, UV radiation, and electrons.

- O_2 plasma increases the number of –OH groups, significantly enhancing surface hydrophilicity and the adsorption of proteins like fibronectin and albumin (Lee et al., 2005).
- NH_3 plasma induces the formation of $–NH_2$ groups, which positively influence osteoblastic differentiation and adhesion (Yoshinari, et al., 2002).

Plasma also removes organic contaminants that naturally accumulate on implant surfaces during storage (the so-called "biological aging" effect) (Deligianni et al., 2001). Plasma treatment is advantageous for being safe, fast, and non-invasive, while preserving surface topography—especially important for delicate structures such as nanotubes.

Laser Texturing

Laser techniques use concentrated light beams (e.g., Nd:YAG, CO_2, or femtosecond lasers) to selectively remove or melt surface material, creating precise micro- and nanostructures. These methods enable the fabrication of reproducible surface textures without the need for chemical agents.

- Laser-created micro-roughness (e.g., grooves, pits, waves) supports cell guidance, enhanced adhesion, and improved organization of the extracellular matrix (Anil, et al., 2011).
- Additionally, laser treatment sterilizes the surface and removes manufacturing residues (Yong, et al., 2013).

Some studies show that laser processing may also enhance the osteoinductive properties of titanium implants, especially when combined with chemical coatings (Scarano, et al., 2006). Although technically more demanding, laser methods are attractive for implantology due to their precision, controllability, and absence of secondary contaminants.

UV Photofunctionalization

Ultraviolet (UV) radiation—particularly at a wavelength of 254 nm—can alter the surface energy of titanium implants through photo-induced oxidation and removal of carbon contaminants. This process, known as UV photofunctionalization, converts hydrophobic surfaces into superhydrophilic ones, dramatically improving cell adhesion and accelerating osseointegration (Aita, et al., 2009).

UV treatment restores the “biological youth” of titanium surfaces, which are otherwise passivated over time by carbon adsorption (Ogawa et al., 2010). Experimental models demonstrate that UV-activated titanium integrates into bone 2–3 times faster than non-activated surfaces (Ueno, et al., 2010). UV photofunctionalization is non-thermal, eco-friendly, and easily applicable in clinical settings directly before implantation.

Ion Implantation

Ion implantation involves injecting high-energy ions (e.g., Ca^+, P^+, N^+, Ag^+) into the implant surface under high voltage. This technique can modify the chemical composition, valence state, surface charge, and biological activity without mechanical damage to the substrate (Huang et al., 2007).

- For example, silver ion (Ag^+) implantation provides a strong antibacterial effect, making it suitable for peri-implantitis prevention (Gugala, et al., 2014).
- Implantation of calcium or phosphorus promotes the formation of calcified matrix and enhances bioactivity.

However, this method requires specialized equipment and is technically more complex than other physical surface treatments (Kim, et al., 2012).

APPLICATION OF BIOACTIVE COATINGS

The application of bioactive coatings to dental implant surfaces represents one of the most promising strategies to improve their integration with bone tissue and increase long-term clinical reliability. Bioactive coatings are specially engineered surfaces that, in addition to their physical and chemical properties, provide biological signals that stimulate cell adhesion, osteoblast proliferation and differentiation, and the formation of new bone matrix. These layers may consist of mineral phases, biological macromolecules, or bioactive nanoparticles.

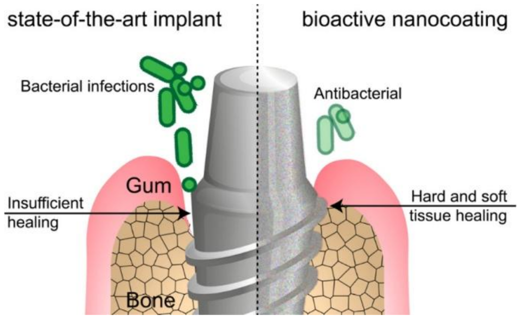

Figure 5. Principle of bioactive coatings (Zhang, et al., 2021).

Hydroxyapatite and Calcium Phosphates

The most widely used bioactive coating in dental implantology is hydroxyapatite (HA), the primary inorganic component of bone and teeth. HA surface layers can be applied using various techniques such as plasma spraying, sol-gel processing, or electrophoretic deposition. Hydroxyapatite coatings enhance osteoconduction, thereby accelerating implant osseointegration (Albrektsson, & Johansson, 2001). Calcium phosphates may also be applied in modified forms (e.g., tricalcium phosphate, fluorapatite), which improve chemical stability and resistance to dissolution in biological fluids. These coatings also stimulate the formation of biomineral phases of the bone matrix at the implant interface (Lee, et al., 2015).

Immobilization of Proteins and Peptides

Another group of bioactive layers involves biomolecular surface modifications through the immobilization of proteins and peptides that naturally promote cell adhesion. A typical example includes RGD peptides (arginine-glycine-aspartic acid), which are components of the extracellular matrix and bind to integrin receptors on osteoblasts (Ruoslahti, 1996). Immobilized proteins such as fibronectin, laminin, or vitronectin enhance specific interactions between the implant and cells, leading to improved proliferation and differentiation of osteogenic cells (Schliephake et al., 2009). These bioactive coatings can be applied through chemical bonding (e.g., via silane linkers) or physical adsorption.

Nanomaterials and Nanostructured Coatings

With the advancement of nanotechnology, research has increasingly focused on applying nanostructured bioactive coatings characterized by a high specific surface area and unique interactions with cells. Titanium nanolayers, calcium nanoparticles, nanoapatites, or collagen nanofibers can be applied using electrophoretic deposition, layer-by-layer assembly, or self-assembling monomolecular films (Zhao, et al., 2010). These nanostructures mimic the natural nanoarchitecture of the bone matrix and provide physical and chemical stimuli that strongly support osteoblastic differentiation while potentially reducing bacterial adhesion Webster, et al., 2000).

Biofunctional Surface Modifications with Biological Factors

Incorporating growth factors and biologically active molecules into the implant surface layer enables localized stimulation of tissue regeneration. The most commonly used include BMP-2 (bone morphogenetic protein-2), which promotes new bone formation, and VEGF (vascular endothelial growth factor), which supports angiogenesis (Schliephake, 2012). These factors can be directly bound to the implant or delivered via carriers such as hydrogels, enabling gradual release and prolonged effect. Such biofunctional coatings significantly improve the potential for rapid and high-quality osseointegration, especially in compromised tissue conditions.

RESULTS AND DISCUSSION

Selecting the appropriate surface modification technique for dental implants is a critical decision that significantly influences the biological response, quality of osseointegration, and long-term clinical success of the implant. Each technique has its own advantages, limitations, and clinical indications, depending on the specific scenario, the type of material used (particularly titanium and its alloys), and the patient's biological profile.

Mechanical techniques such as sandblasting and acid etching (especially the SLA technique – sandblasted, large grit, acid-etched) are currently considered the gold standard for routine clinical applications. They create micro- and macro-scale roughness, increasing surface area, improving mechanical anchorage of the fibrin network, and promoting early osteoblast colonization (Wennerberg & Albrektsson, 2010). Their advantages include proven long-term clinical reliability and ease of process reproducibility. However, disadvantages include the risk of residual abrasive particles and limited ability to actively modulate biological processes, which is particularly important in patients with impaired healing capacity (e.g., diabetics, smokers) (Chrcanovic, et al., 2015).

In contrast, chemical treatments such as anodization or alkaline treatment with heat processing deliberately modify the surface's chemical and electrical properties, enhancing its reactivity and promoting early-phase apatite formation during healing (Kokubo & Takadama, 2006). These techniques create a bioactive interface capable of ion exchange and selective protein adsorption. Additionally, they allow for the integration of functional groups that can influence the direction of cellular differentiation. Potential drawbacks include higher technological demands and the need for precise control over processing conditions (Sul, et al., 2002).

Physical methods such as plasma treatment or laser texturing can alter surface energy and nanostructure without direct material contact. Plasma activation significantly increases surface hydrophilicity, promoting the initial adhesion of osteoprogenitor cells and the expression of osteogenic markers (Canullo, et al., 2017). Laser texturing, on the other hand, enables the creation of precisely defined micro- and nanopatterns that influence cytoskeletal arrangement and cell morphological orientation (Scarano, et al., 2003). These methods appear promising, especially in personalized implantology, but require sophisticated equipment and standardized parameters. The application of bioactive coatings such as hydroxyapatite, bioglass, or biologically active molecules (e.g., RGD peptides, BMP-2) provides an additional level of interaction between the implant and host tissue. These coatings can actively stimulate osteoblastic differentiation and angiogenesis (Hench, 2006; Schliephake, et al., 2009). While plasma-sprayed HA coatings previously suffered from delamination and low adhesion to titanium, modern techniques such as sol-gel or electrophoretic deposition have significantly improved the quality and stability of these layers (Geetha, et al., 2009; Lee, et al., 2015). Their main limitations include potential immunological reactions or degradation of the coating under dynamic oral loading. Overall, there is no universal technique suitable for all clinical scenarios. Rather, an individualized approach is needed, considering the characteristics of host tissue, expected healing duration, presence of risk factors, and properties of the implant system used. Current trends favor multimodal strategies that combine multiple techniques (e.g., SLA + plasma activation + bioactive coating) to achieve synergistic stimulation of the biological response (Gomez-Florit, et al., 2021).

Table 1. Comparison of Dental Implant Surface Modification Techniques.

Technique	Description/ Principle	Advantages	Disadvantages	Indications
Mechanical Modifications (sandblasting, etching, SLA)	Creation of micro- and macro-roughness using abrasives and acids.	- Increased surface area - Enhanced fibrin anchorage -Early osseointegration - Proven clinical reliability	- Risk of residual abrasives - Low biological activity - Unsuitable in cases of impaired healing	Routine use, suitable for most patients
Chemical Treatments (anodization, alkaline and heat treatment)	Modification of chemical properties to promote cell adhesion and differentiation.	- Higher surface reactivity - Promotes apatite formation - Integration of functional groups	- Technologically demanding - Requires precise process control	Patients requiring enhanced bioactivity
Physical Methods (plasma, laser)	Non-contact surface nano-structuring to modulate cellular responses.	- Increased hydrophilicity -Precise micro/nanotexturing - Promotes cell orientation	- Requires sophisticated equipment - Need for parameter standardization	Personalized implantology, experimental applications
Bioactive Coatings (hydroxyapatite, bioglass, RGD, BMP-2)	Deposition of bioactive substances to stimulate cell activity.	- Osteoblast stimulation - Biocompatibility	- Risk of immune reactions - Coating degradation	Complex cases, patients with impaired healing

CONCLUSIONS

Surface modifications of dental implants play a crucial role in ensuring their biological compatibility, mechanical stability, and long-term clinical success. Given the diversity of materials used, each implant type requires a specific approach that considers its physical, chemical, and biological characteristics. Mechanical, chemical, and physical surface modification methods significantly influence the topography, surface energy, and chemical composition, directly enhancing cell adhesion, osteoblastic activity, and subsequent osseointegration. The application of bioactive coatings, including hydroxyapatite and nanostructured layers, represents an advanced strategy to increase implant bioactivity and stimulate bone tissue regeneration. In addition to supporting bone integration, appropriately selected surface treatments can modulate inflammatory and immune responses, thus reducing the risk of complications such as peri-implantitis. A key aspect is the individualization of surface modifications based on specific clinical conditions and patient-related systemic factors, including bone quality, the presence of chronic diseases, and other risk factors.

The future of dental implantology lies in the development of intelligent, multifunctional surfaces capable of adaptively responding to changes in the biological microenvironment, thereby improving implant functionality and longevity. The integration of advanced material technologies with clinical strategies leads to optimized treatment outcomes and improved patient quality of life. A systematic connection between experimental research and clinical practice is essential for the effective translation of innovations into routine use in implant dentistry.

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DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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